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Engineering Note

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Author

Sandor Feher, FNAL, Amalia Ballarino, CERN
Jon Zbasnik, LBNL Jon Zbasnik 2/20/02

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MHL

Prototype 7500 A HTS Current Lead Test Report

Content:

1. Overview

The prototype leads arrived at CERN on Tuesday November 6th. Using Procedure M8041, shown in Appendix A, inspection started the same day and it was finished on the next day. Mechanical and electrical integration of the leads into the LBNL top head took 5 working days. Insertion of the top plate into the dewar followed by cryogenic inspection and system checkout lasted another day. The first cool down occurred on Wednesday 11/14/01. After two days of measurements we warmed up the cryostat to achieve full thermal cycle of the leads during the weekend. The leads were cold again on Monday November 19th. The test continued with further DC operation, quench and helium coolant loss measurements. The test was finished on 21st of November 2001. The testing was conducted by A. Ballarino, D. Milani, V. Fontanive, from CERN and S. Feher from FNAL. The testing was partially witnessed by the manufacturers of the lead, D. Spiller from Pirelli, and C. Beduz from University of Southampton.

2. Inspection of the leads

Pirelli inspection and Test Record were shipped with the leads. The records contained factory test results of the finished leads, component tests, and material certifications but did not contain a record of critical steps in the manufacturing process and in-process tests to document that the critical steps were done properly.

General condition of the shipment container and the leads in the container had no sign of any damage. The g-load indicator was intact. Orientation of the warm terminals and mounting flange were as required and the 20 K inlets were on the opposite side of the warm terminal. Both conflat knife edges were nice and smooth. 20 K inlets were 502 mm below the top flange. The LBNL (20 K) seal flanges were 560/562 mm below the top flange and their surfaces finishes were in excellent shape (the flatness of the leads seal flanges were not measured). The outer diameter of the flanges was 130 mm. The HTS sections were 455 mm long and the over all length of the leads was 1450 mm. The minimum and maximum liquid levels were not labeled, so we made marks on the leads according to the LBNL specification. The perpendicularity and parallelness of the leads will be measured at LBNL. Voltage tap continuity checks and the lead thermometer resistances were made as they were specified for both leads. All the instrumentation was found to be properly connected.

3. Mechanical and electrical integration of the leads into the top hat

First the chimney was positioned vertically, so the top hat was tilted by ~10 degrees. Then the baffle assembly was installed onto the lead. The peek seal and the two Kapton covered G10 tubes were positioned into the chimney. The technicians made two teflon rings that should help to center the seal with respect to the chimney. After installing the rig support structure onto the flag and cleaning all the relevant surfaces with alcohol we lifted the lead with a crane. Before lowering the lead into the chimney we put the copper gasket on the flange at the chimney side. Lowering the lead was a smooth operation. We installed the teflon rings to keep the lead in the center. Tightening down the 20 bolts didn't work since the gasket was falling out of the groove and we were not able to center the gasket relative to lower flange knife-edge. First the technicians were suggested to glue the gasket down to the upper rectangular groove. However, another technician had another idea. He thought, the gasket can be hit a little bit so forming it to a slightly oval shape, then it can be tapped into the groove. Before he consulted it with us he did it and it worked, the gasket stayed in position. Tensioning the bolts was an easy exercise once we understood the procedure. The only confusion was due to the misinterpretation of the role of the gap between the Belleville washer assembly and the top of the flange. **There is a strong recommendation to add a stopper about the right elevation to the Belleville washer housing, so no one can tighten the washers more than the specified value.** Otherwise a damage can be made to the leads if more tension is applied than what is necessary. After leak checking of the chimney was completed the clamp and the support structure for the LTS cable was installed. We paid particular attention to ensure that the superconducting part of the cable are facing each other. The cable was also wrapped tightly with Kapton tape. Indium foil was placed between each cable, and a clamp was used to hold together the joint. The tightening torque was 20 N m. The V6- voltage tap wires were soldered to the LTS cables close to the bottom end of the current lead. The wiring schematic is sown in Figure 11. We also paid attention to use Belleville type washers attaching the cable support structure to the leads. This ensured that after cool down the pre-stress of the G10 support structure holding the clamp with the LTS joint will be maintained. After the temperature sensor located at 20 K helium gas inlet was wired, the leads were inserted into the test cryostat. At this point also electrical checkout took place. The huge buses were connected to the leads after the leads were cold and the high voltage stand off test was completed.

4. Cool down

We followed the cool down procedure CERN developed for their prototype leads tests. First the cryo-distribution box was cooled down, then the outer shield of the cryostat. At last the dewar which contains the leads were filled with liquid helium. Filling the dewar and cooling the copper section of the leads had started at the same time to prevent too high temperature gradients across the leads. Figure 1 shows the temperature of the upper HTS terminals and the inlet helium gas as a function of time for the leads.

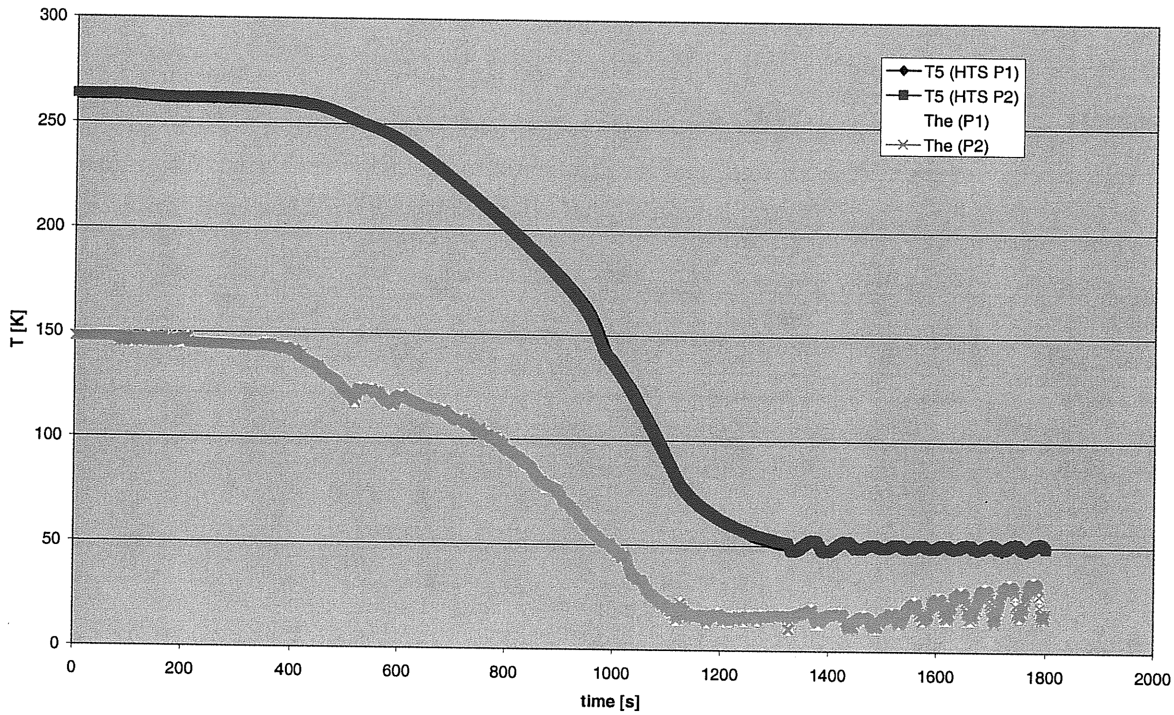

Figure 1. Inlet temperature of helium gas cooling the resistive part (The) and upper temperature of HTS (T5) during cool-down

5. High voltage stand off measurements

During cool down the buses were not connected to the leads to allow us to perform high voltage stand off tests right before and after cool down. The CERN high voltage stand off instrument is not capable of measuring leakage current. However, it monitors the leakage current. If the leakage current becomes higher than a threshold set by the user, the high voltage is instantaneously turned off. By setting different threshold values one can determine the range of the leakage current. At room temperature and 1 atm helium environment and 1 μA threshold setting we were able to hold the high voltage at 1500 V without tripping the power supply. After cool down we also performed a high voltage test. This time the leakage current was slightly higher: 1 μA $<$ I(leakage) $<$ 5 μA.

Since the specification calls for less than 100 μA (for the pair) the leads meet the HV stand off requirements.

6. Heat load measurements

The heat load measurements without current were performed during two nights. With current we performed one measurement at 7500 A. The basic concept of the measurement was to measure evaporation rate. In order to get more precise measurements the evaporation rate was obtained indirectly by measuring the rate of the liquid level change after reaching a steady state condition. The following values were obtained:

Without current applied 0.788 ± 0.050 W
At 7500 A current applied 1.030 ± 0.050 W

7. Joint resistance measurements

Joint resistance measurements were performed using a Keithley voltmeter to get high resolution in the low voltage region. The current was ramped up with stair steps of 1000A up to 7500 A. At each step the current was held for 15 minutes and the data was collected with approximately 1 Hz rate. These measurements are shown in Figures 2 and 3. The results are summarized in table 1.

Table 1. Contact resistance at 7500 A.

	Resistance [nΩ]	
	Lead 1	Lead 2
HTS-Copper joint (T≈50 K)	73	70
HTS-LTS joint (T≈ 4.5 K)	9.3±1.5	4.4±1.5
LTS-LTS joint (T≈ 4.5 K)	4.0±1.5	

The total heat load into the helium bath due to joint resistances were estimated to be ~ 1 W.

The resistance of the HTS-LTS joint is specified to be < 5nΩ, and Lead 1 shows a contact resistance that is almost twice the specified value.

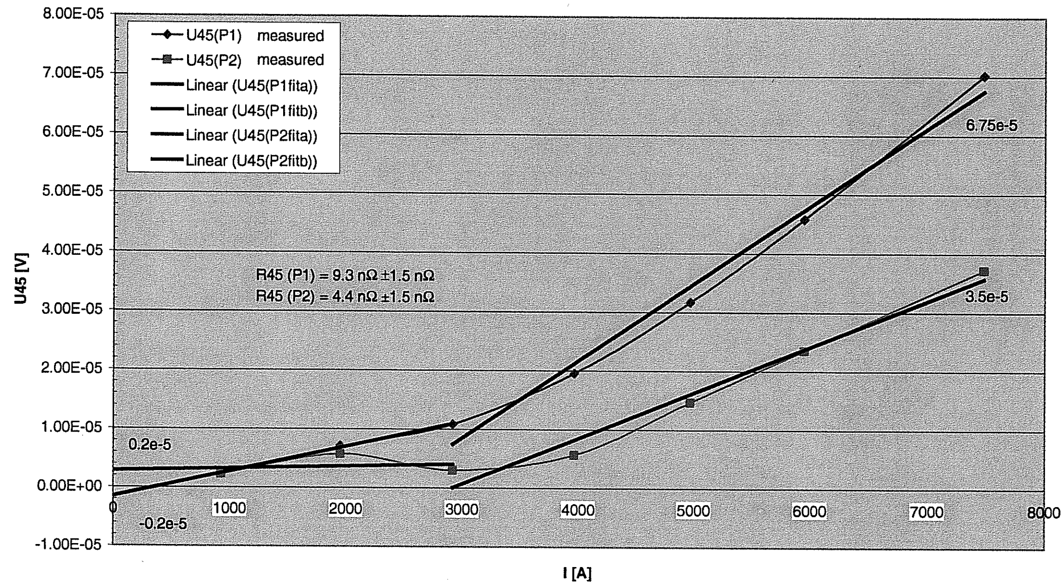

Figure 2. HTS and LTS joint voltages (U45) as a function of current

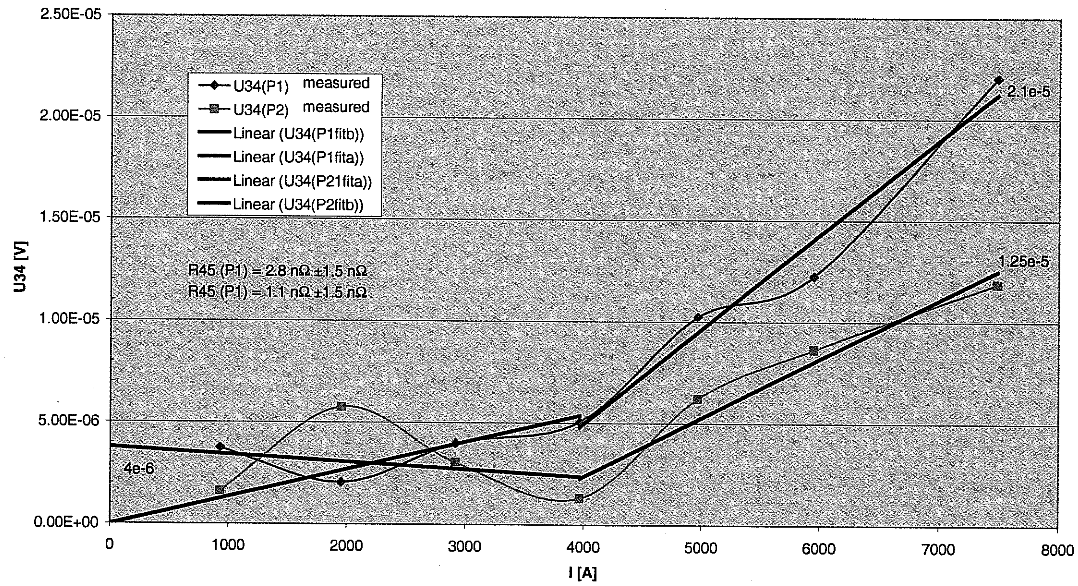

Figure 3. HTS and copper section voltages (U23) as a function of current

8. DC operation

The main purpose of these measurements was to test the performance of the lead under long term operation and at different operational conditions.

8.1 Nominal operation.

The helium gas inlet temperature was set to 20 K. Helium flow rate was adjusted to maintain the upper HTS terminal temperature at about 50 K. Current was ramped up to 7500 A. The leads were operated several hours without showing any sign of instability. No moisture accumulation was seen on the lead while it was seen on the lead conflat warm flange. The average flow rate was 0.45 g/sec for both leads, which were in good agreement with the LBNL specifications. The voltage drop for both leads was in the order of 70 mV. The two lead voltages agreed within 1%.

However we noticed that the temperature reported by T3, which is located at the "burnout" point differed between the two leads (see Figure 4). The temperature of one of the leads was about 30 K higher than the other one. There were several possible explanations for this temperature difference: a) non uniform cooling along the lead, b) uneven copper material properties, c) extra heating close to the top of the lead probably due to bad copper to copper connections: adaptor to cable, cable to lead flag, or inside the lead, or d) bad temperature sensor. Possible cause d) can be ruled out because we noticed a temperature difference at 0 current lower than that at 7500 A ($DT \approx 30$ K at 7500 A and $DT \approx 6$ K at 0 A). The most likely explanation at this time is c). This indicates that the manufacturer should develop a method to check the resistive joint characteristics before they make the final lead assembly.

We saw no appreciable difference in the temperatures reported by T1 and T2 (< 2 K).

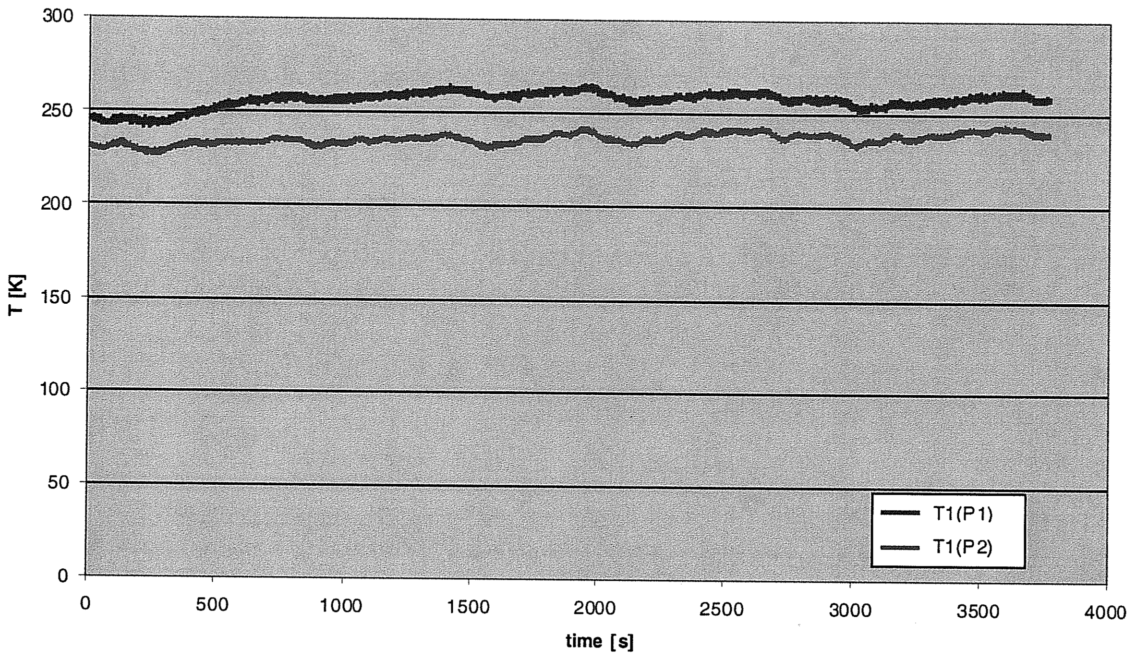

Figure 4. T3 temperature (i.e. the upper temperature of the resistive part) of the two leads at nominal condition

8.2 Reduced flow rate test.

This test was essentially the same as the previous one but the goal was to apply 5% less helium flow rate and verify that the leads were able to operate at nominal current without suffering thermal run-away. It turned out that it was hard to set a steady flow rate with such precision. We made the following change: the temperature of the HTS section was increased to about 58 K and the PID loop was controlling the flow rate. In this way we were able to maintain lower and more stable helium flow rate. The flow rate corresponding to this setting was approximately 0.42 g/sec. At this flow rate the copper section voltages increased to 84 mV but the lead operation was stable for a period of about 1 hour.

8.3 Reduced inlet gas temperature test.

In this test we set the inlet helium gas temperature at 10 K but rest of the settings were the same as in 8.1. As it was expected, to keep the 50 K setting of the upper HTS terminal the flow rate had to be reduced slightly. Consequently the copper section temperatures and voltages increased as well. The performance was similar as in 8.2 since the helium flow rate was around 0.42 g/sec. Also there was no sign of operational instability of the leads.

9. Response to loss of 20 K coolant flow

Author
Sandor Feher, FNAL, Amalia Ballarino, CERN
Jon Zbasnik, LBNL

First we set the nominal operational conditions for the leads. The inlet helium gas temperature was set to 20 K, and the upper HTS terminal temperature was kept at 50 K. The applied current was 7500 A. After reaching stable operation (~15 minutes) we performed the coolant loss test by shutting down the helium flow for one of the leads at a time. The threshold for the protection system of the copper (HTS) section was set to 100 mV (5 mV). For both leads the coolant loss was observed by the protection system. The copper section voltage has reached the 100 mV value before the HTS section became resistive. The maximum value of the upper HTS terminal temperature was close to 70 K. Figure 5 shows the voltage across the resistive sections and terminals due to interrupted 20 K cooling flow to Lead 1. C1 represents the voltage drop across the resistive part of lead P1, C3 the voltage drop across the resistive part of lead P2 and C5 the total voltage drop between the two leads (from warm to warm terminal), as shown in Figure 11. Figure 6 shows the voltage developed across the heat exchanger section only due to a stoppage of the cooling flow.

During these tests the HTS part of the leads did not quench .

Operating the lead again at nominal conditions demonstrated that the lead performance has not been compromised by the coolant loss test.

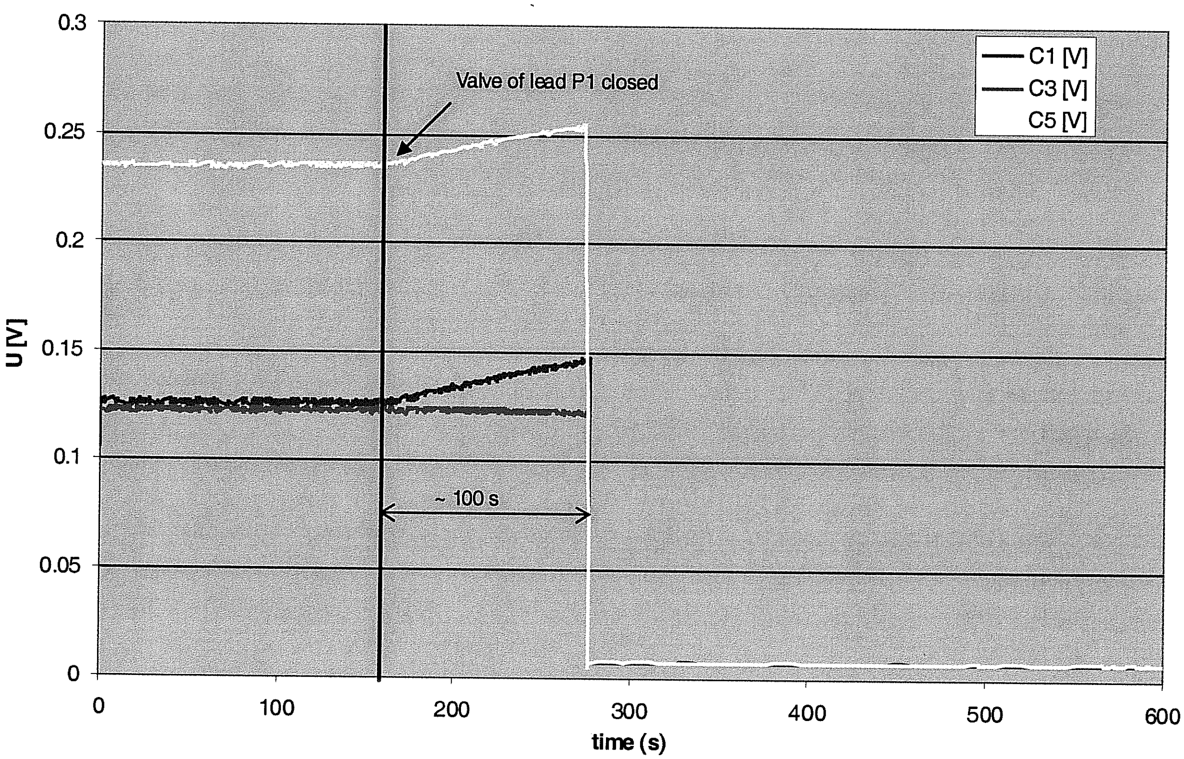

Figure 5. Voltage drop across the resistive part of the lead (coolant loss test on lead P1)

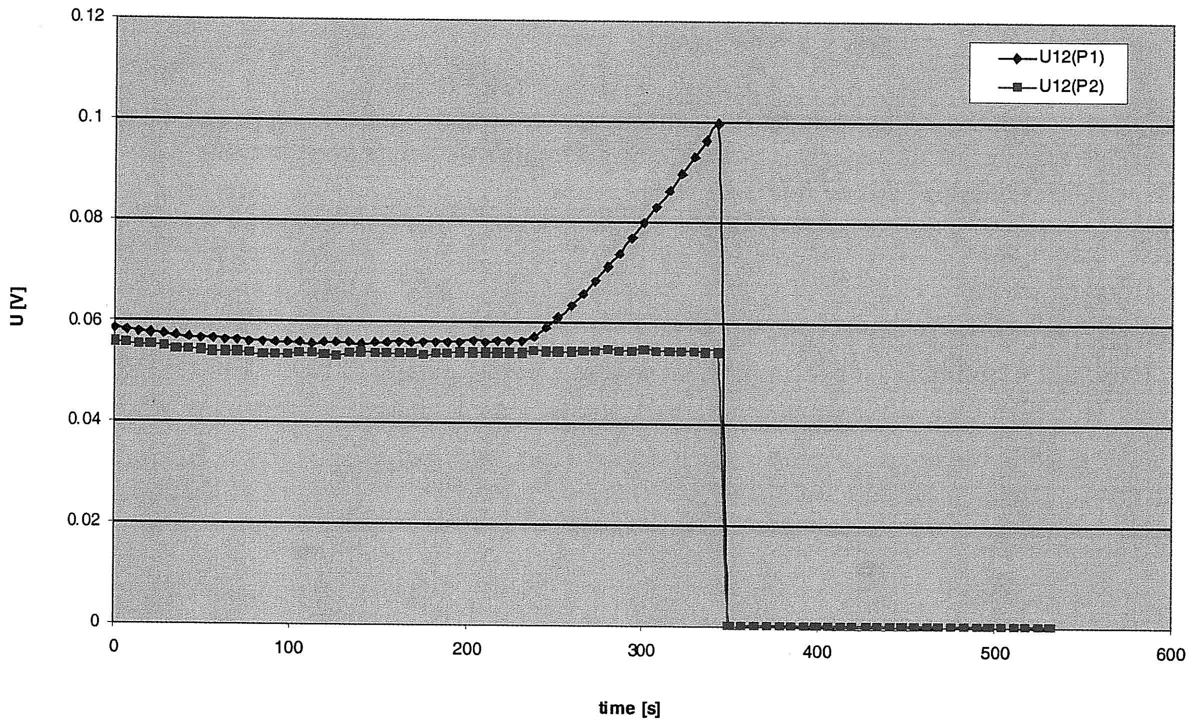

Figure 6. Voltage drop across resistive part (U12)

10. Driving the HTS part into resistive mode

In this test the goal was to demonstrate that the leads can survive HTS quenches. To drive the lead into the resistive mode we increased the HTS terminal temperature by increasing the inlet helium gas temperature (see Figure 10). We also had to increase the flow rate to maintain stable operation of the copper sections. Both the HTS and the copper section protection voltages were set to 100 mV. The HTS section reached the 100 mV value when the upper HTS terminal temperature was about 90 K. The peak temperature of the HTS upper terminal was measured to be 96.5 K on lead P1 and 99 K on lead P2. The voltage drop measured across the HTS part at quench detection was 0.1 V on lead P2 and 0.05V on lead P1. The voltage drop across the HTS increased from 5 mV to 100 mV during about 40 s (see Fig. 7). When the voltage reached 100 mV, the current was ramped down at about 500 A/sec to simulate an exponential current decay of 12 second time constant by the quench protection system. The quench did not propagate further on HTS (see Figure 8). Figure 9 shows the voltage drop across the connection between the copper and HTS section as the inlet helium temperature is increased to drive the HTS section normal.

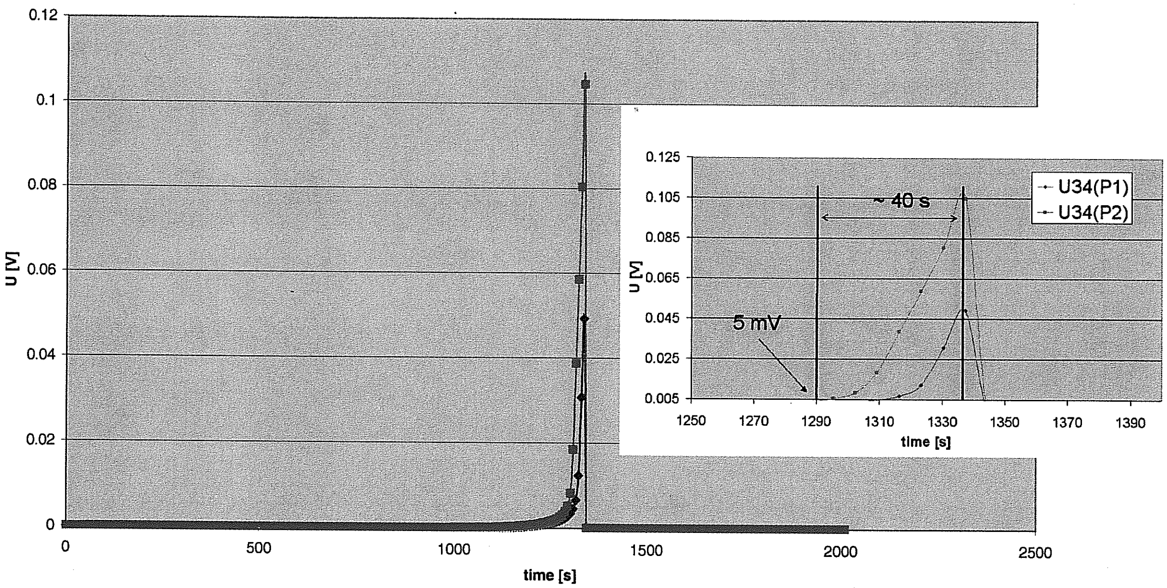

Figure 7. Quench of HTS in lead P2. Voltage drop between top and middle of HTS part

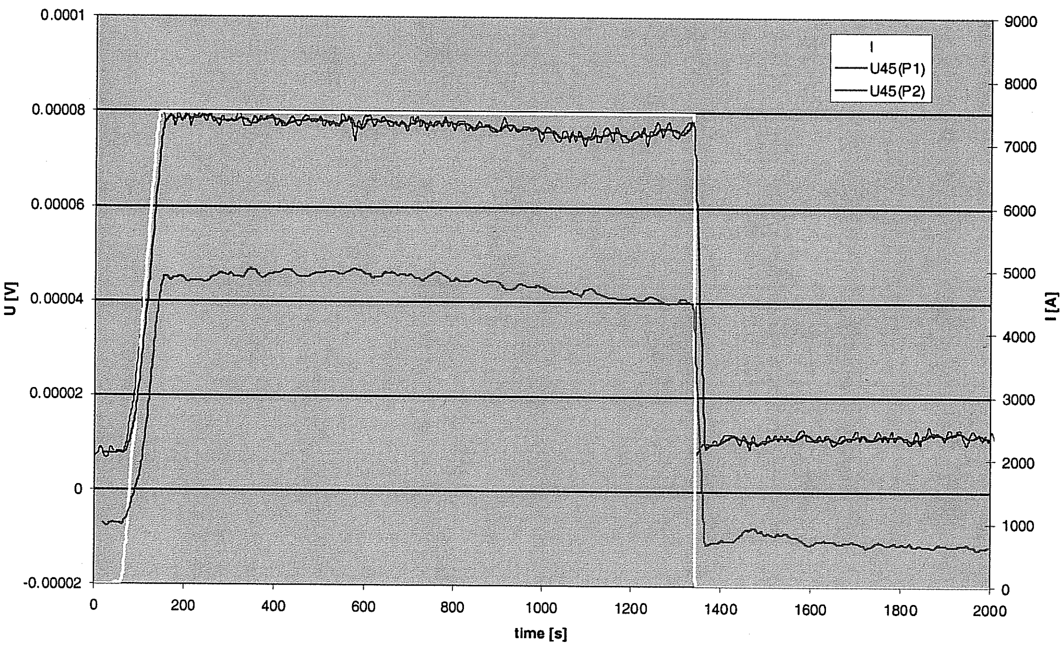

Figure 8. Quench of HTS in lead P2. Voltage drop between middle and bottom of HTS part

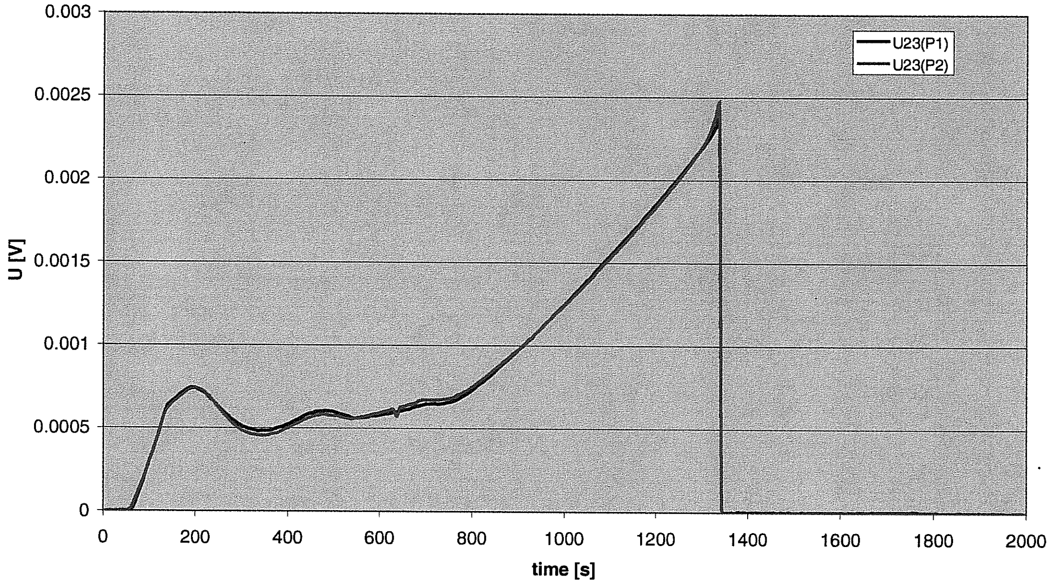

Figure 9. Voltage drop across the resistive part (U23)

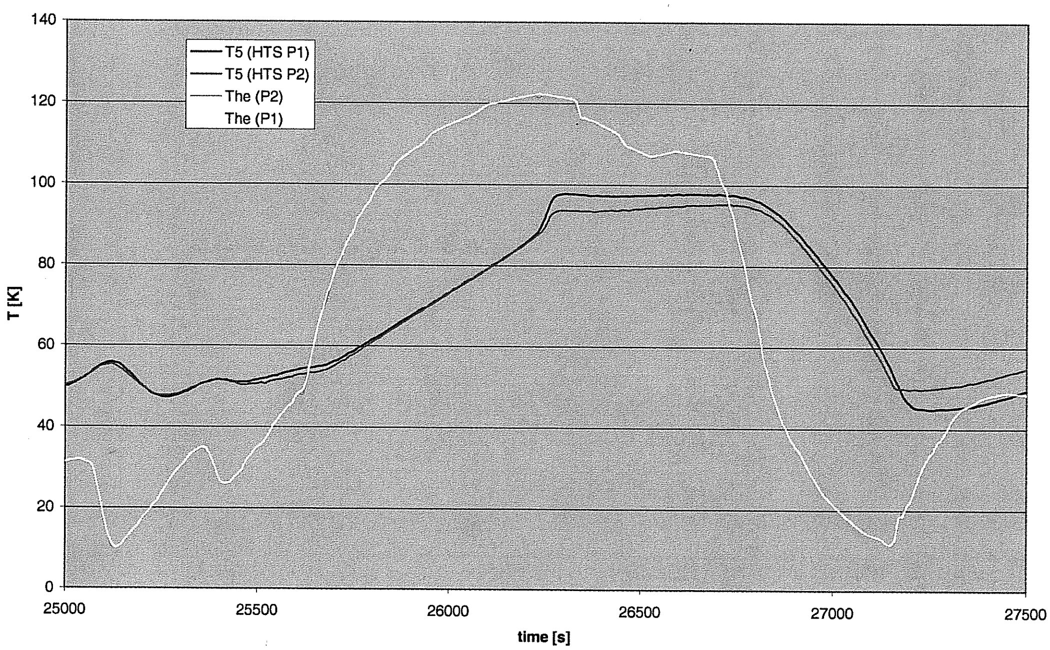

Figure 10. Inlet helium temperature and upper HTS temperature during quench transient (T5 and The for lead P1 and P2)

Author
Sandor Feher, FNAL, Amalia Ballarino, CERN
Jon Zbasnik, LBNL

11. Performance after thermal cycling the leads

On the weekend the leads went through complete thermal cycle. The HTS terminal temperatures were at 265K and 266K before we cooled down the leads the second time. The operation of the leads was the same as at the first thermal cycle.

12. Summary

The leads in general performed very well and except for joint anomalies were in compliance with Specification M923B. The joint anomalies do not appear to significantly affect lead performance, but they raise concern about possible future problems. There appear to be no great differences between T1 which is fixed in place with epoxy and T2 which is removeable.

The heaters integrated at the top of the lead have been tested and they proved to work fine. No condensation was seen at the top of the lead in any operating conditions.

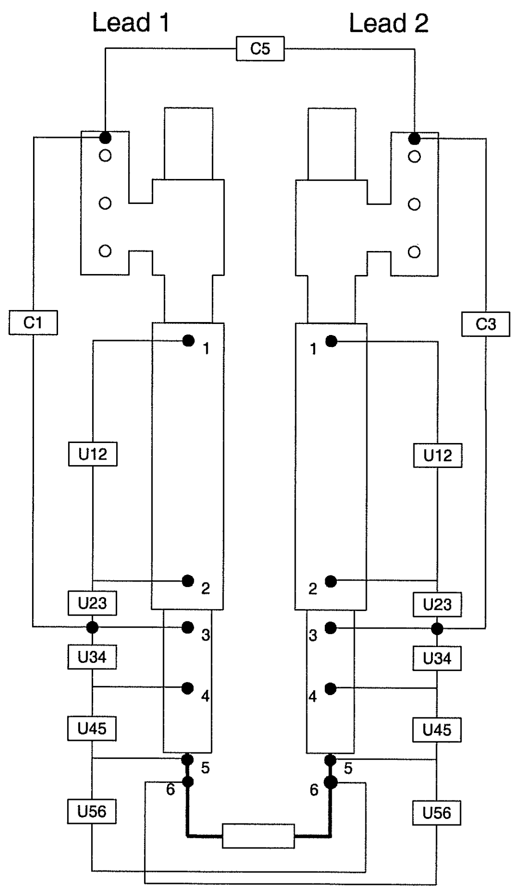

Figure 11. Wiring Schematic. Points 1 and 2 are on the copper section, 3 and 4 are on the HTS section, and 5 and 6 are on the LTS portion.